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ABSTRACT

The purpose of this study was to investigate the nature of scientific explanations used in science education. Science educators agree with philosophers that explanation is the very purpose of science itself and explanation tasks are commonly used to assess students' understanding. However, little research is done on the nature of the explanations given by individuals who have received formal science instruction. A review of the views on explanation expressed by philosophers, physicists, and science educators suggests that these groups not only hold different perspectives, but they are concerned with different aspects of the problem. Philosophical analyses highlight the pragmatic factors involved in explanations as well as their logical structure. Physicists view explanations as part of "playing by the rules" of the scientific domain which are very distinct from the rules used in everyday domains. Studies in the nature of explanation in science education stand on looser philosophical grounds. These studies are naturally interested in types of teaching explanations and in students' explanations, which represent diverse groups of individuals with very different characteristics and in many different settings. Findings suggest that the potential in this area of research has yet to be recognized. Contains 41 references. (Author)

What Constitutes a Scientific Explanation?

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Abstract

The purpose of this study was to investigate the nature of scientific explanations used in science education. Science educators agree with philosophers that explanation is the very purpose of science itself and explanation tasks are commonly used to assess students' understanding. However, little research is done on the nature of explanations given by individuals who have received formal science instruction. A review of the views on explanation expressed by philosophers, physicists, and science educators suggests that these groups not only hold different perspectives, but they are concerned with different aspects of the problem. Philosophical analyses highlight the pragmatic factors involved in explanations as well as their logical structure. Physicists view explanations as part of playing by the rules of the scientific domain which are very distinct from the rules used in everyday domains. Studies in the nature of explanation in science education stand on looser philosophical grounds. These studies are naturally interested in types of teaching explanations and in students' explanations which represent diverse groups of individuals with very different characteristics and in many different settings. Findings suggest that the potential in this area of research has yet to be recognized.

What Constitutes a Scientific Explanation?

Introduction

The purpose of this paper was to examine the nature of scientific explanations used in science education. How do we deal with scientific explanations in science education research and practice? The question "What is a scientific explanation?" is investigated from the points of view of philosophers, research scientists, and science educators. Selected studies illustrate the contrasting views on explanations held by researchers in science education whose concerns are primarily related to physics, education, philosophy, or to the complex interplay between these domains. Empirical findings about the nature of scientific explanations generated by various individuals are reviewed.

Significance

"Scientists strive to make sense of observations of phenomena by inventing explanations for them that use, or are consistent with, currently accepted scientific principles." (Rutherford and Ahlgren, 1990). The generation of scientific explanations is an important learning goal in school science. Yet, there are no clear criteria for scientific explanation of natural phenomena in science education. Although philosophers of science dealt extensively with this topic, a number of questions arise for science education: How relevant are philosophers' models of explanation for practicing scientists? To what extent to they serve science education research? Do science educators have clear notions and criteria for scientific explanation? Are these notions shared by teachers, curriculum makers, examiners, and other practitioners? What are the characteristics of explanations developed by students at different ages?

Students' explanations of natural phenomena have been traditionally used for assessment of their understanding and for designing instruction (Champagne, Gunstone, & Klopfer, 1985; White & Gunstone, 1991). Yet, a coherent framework is needed for research on scientific explanation. Insights from scientists, teachers, and students highlight the complexity of the variables related to this issue for science educators. Insights from the philosophy of science enable us to analyze the structure and nature of the knowledge involved in explanations offered by various individuals in different contexts.

Design and Procedures

In collecting the studies used in this review, a search was initially conducted on the ERIC computerized data base, using combinations of the keywords "explanation", "teacher", "student", "scientist", "understanding", and "knowledge". References that were listed in the retrieved studies were also tracked and reviewed. In addition, "classic" studies in the philosophy of science provided a frame of reference and an analytical background for this review. Likewise, several articles in the *American Journal of Physics* and in *The Physics Teacher* dealing with the explanation of natural phenomena were examined.

Explanation and Philosophy

What is an Explanation according to Philosophers?

Since explanations are not only of something but for someone (Mc Ewan & Bull, 1991), the range of possible explanations that can be provided to a given question depends on the knowledge available to the explainer and the knowledge assumed to be available to the explainee. Achinstein (1971) included these pedagogical considerations in a general model stating that an *explanation* (E) depends on *who* (A) explains, *what* (q), *to whom* (S). E may be a fact, a sentence or anything else that a person in S will find "illuminating". The criteria for a satisfactory explanation E require that S understands q: They depend on the knowledge and concerns of those in *S* including relevance, correctness, and depth. This model can be represented in short as $E=f(A, q, S)$[1].

This paper is concerned with the particular case where *q* is a question of the type "why (or how) some phenomenon happens" in a context of inquiry in natural science. However, in addition to the requirement that the explainee *S* understand, the explainer *A* may have additional or different criteria for satisfactory explanation. Since *A* giving an *E to S* requires that *S understands*, the question what it means to understand arises. Obviously, the reflexivity of the relationship between *explain* and *understand* cannot be ignored. However, this discussion will be limited to the set of objects of explanation to *observable phenomena* by *scientific* arguments, postulating with Suthers (1993) that the explainer negotiates the structure of the domain knowledge to make trade offs between informativeness, comprehensibility, and integrability. Although this review attempts to focus on the scientific explanations of natural phenomena, the situation, context, goals, and interaction between explainer, explanandum, and explainee need to be considered.

What is a Scientific Explanation according to Philosophers?

Having defined *what* is to be explained, *by whom* and *to whom*, the question of common criteria for science (for what purpose is the explanation developed?) still needs to be addressed. In the case of scientific explanation of natural phenomena, the goals of science and its culture determine these criteria. Scientific explanations of natural phenomena may be considered to be a particular case of the A, q, S, E model, where q is the question "Why <a phenomenon> occurs, and A and S share a common knowledge, language, culture, in a scientific domain. Logical empiricists have focused on the relationship between the explanandum and the explanans from a logical point of view. Other philosophers (e.g. Kuhn, Feyerabend) emphasize the problems associated with the definition of the explanandum and the adequacy of the explanatory schemes. They stress the importance of background theories in the interpretation of experience and in the production of descriptive statements.

The D-N model.

Hempel and Oppenheim's (1988/1948) famous paper provides the foundation for discussions on scientific explanations till this day. First, it poses that science includes a requirement that the explanation be not only psychologically satisfactory (for example giving a sense of homeness created by a metaphor or a reduction to the familiar) but that the phenomenon (q) can be accounted for by the application of relevant scientific knowledge. Focusing on the logical structure of arguments that constitute scientific explanations, Hempel and Oppenheim developed the *deductive-nomological* model (known as the D-N model), where a descriptive statement of the phenomenon is derived from statements about the particular case combined with the applicable theory.

C_1 C_2, ... C_n	Statements which make assertions about particular facts
L_1 L_2, ... L_n	General laws and other statements
DEDUCTING PREDICTION	Conclusion of the argument is the explanadum sentence

Outline of the deductive-nomological (D-N) model for scientific explanation (according to Hempel and Oppenheim (1988/1948)

In this model, the explanation is formulated as a "deductive argument whose conclusion is the explanandum sentence, and whose premise-set, the explanans, consists of general laws (L_1, L_2, ... L_k) and other statements (C_1, C_2, ... C_k) which make assertions about particular facts"

[1] q = What is explained
A = Who is giving the explanation
S = Who is receiving the explanation
Criteria for a satisfactory explanation include that "S understands"

(Hempel, 1966, p. 51). The D-N model also requires that all the sentences involved in the argument have some empirical foundations: the laws invoked, the assertions, and the explanandum sentences must be acceptably related to observations. Hempel also proposed that a more sophisticated type of explanation (derived from the D-N model) is the theoretical explanation. Based on theoretical principles, theoretical explanations are considered to be more satisfactory because of their depth and their predictive power. This model can be expanded to probabilistic explanation when the laws in the explanans are probabilistic statements rather than universal statements.

Beyond the D-N model.

An oversimplified interpretation of the D-N model and its support for theoretical reduction may lead to reject it for associating it with objectivism, positivism, or reductionism, or other ideals that would be based on dualisms which have been abandoned since Quine's *Two Dogmas of Empiricism* (1953). When descriptive statements ($C_1, C_2, \ldots$) are considered to be theoretical interpretations of observations, the discourse on scientific explanations raises questions about the meaning and foundations of so called scientific facts. (Feyerabend (1958, 1962, 1965, 1975) for example applied these holistic arguments extensively).

Nevertheless, the purpose of scientific explanations according to philosophers remains to subsume some representation of the explanandum to accepted scientific theories which are presumed to be applicable in a particular case. Yet, as Van Fraassen (1988/1980) remarked, scientific explanation is not (pure) science, but the application of science. In many cases, the validity of the laws or theories invoked is not challenged. Instead, the foundations of the explanandum sentence, assertions describing the explanans, or the applicability of a theory may be questioned.

Scriven (1988/1962) summarized complementary aspects of scientific explanations in seven points, for considering explanation as: (a) answers to "why" questions; (b) more than descriptions; (c) essentially similar to predictions; (d) sets of true statements; (e) explanations as involving descriptions of what is to be explained; and (f) the distinction between explanations and the grounds for explanation; (g) completeness of explanations. These are not alternative models but complementary aspects to be considered.

In Conclusion (for Philosophy)

Philosophers deal with explanations from ideological and historical perspectives. Their goal is primarily to produce sociological, historical, or logical reconstruction of science and theoretical models for scientific growth. But they do not deal with these issues at the scale of daily work of individual scientists. They do not deal with the "normal" use of theories in school-learning situations either. However, the question "how individuals (scientists and others) determine the explanandum and the explanans" is an important one for science education; and its investigation can benefit from the analytical discussions above. Discussions of the D-N model provide a useful framework for the investigation of scientific explanations at all levels.

Scientific Explanation and Physics Research

Nature of Scientific Explanation in Physics Research Journals

In the physics literature, articles explaining natural phenomena are frequently published in physics teaching journals These for the most part use mathematical tools to treat the phenomena. Representative examples include *Why do tides exist?* (Withers, 1993) and *Big Ben on a shoestring* (Kalotas & Lee, 1993). Such articles describe the equipment and methods of producing the phenomenon, then they present a mathematical model and its application to these particular conditions. The mathematical arguments can be shown to fit the logical structure of the D-N model. Articles addressing a more research oriented audience traditionally deal with the adequacy, limitations, and simplifying assumptions of alternative models. (e.g. Chapman, 1960 or Reinsch (1994). However, studies of this sort are written and read in the "physics culture", where criteria for explanation, its nature, etc. are implicitly shared in a working context. They do not address philosophical questions that arise in education regarding the learning of these implicitly shared cultural elements.

Views of Scientific Explanation by Research Physicists

Physics education researchers views.

Reif and Larkin (1991) defined the central goal of science as "explaining and predicting parsimoniously as many observable phenomena as possible" (p. 741). Their ideal of explanation includes fundamental aspects of the D-N model: In their view, both explanation and prediction involve the same logical inferences.: "... predictions ... involve inferences from basic premises to observable phenomena ... explanations involve inferences showing how observable phenomena can be deduced from basic premises" (p. 741-742). Their discussion of understanding still implies that there is no absolute or ultimate explanation: "Different theoretical premises may be used as the basis of understanding -- depending on what is possible or desirable" (p. 742). They cite for example that there are multiple ways of explaining the properties of a gas according to macroscopic thermodynamic theory or according to atomic theory and statistical concepts.

Empirical studies of physicists views.

In a study based on interviews and ethnographic observations with 20 physicists, Becher (1990) found that they viewed physics as a sophisticated discipline seeking "to develop models of natural phenomena by the use of mathematical techniques". But they specified that it is: "the concepts and their relationships with each other and with reality which is at the heart of the subject". The physicists pointed out that uncertainty was inherent to all conclusions of solutions because these were achieved by "simplifying the problem, neglecting some effects, averaging over others, and so on". Consistent with Reif and Larkin's concept of parsimony, Becher remarked that physicists also applied terms of appraisal like "elegance in a solution" and "economy of explanation" to the product of their work. In the physics community, solutions that meet the requirements for theoretical and experimental adequacy are also judged by criteria of power and of esthetics.

An empirical study (Edgington, 1995) indicated that research physicists views are consistent with the emphasis on alternative explanatory models and their limitations. Finally, a personal testimony illustrates and summarizes the point: In one lecture[2] about the unifying theory that I attended, Steven Weinberg asked repeatedly about every development he presented "*Of what problem is this the solution?*".

In Conclusion (Physics Research)

Research scientists' ideal of explanation includes elements of the D-N model (predictions, inferences from basic premises to observable phenomena), combined with the assertion that "different theoretical premises may be used ... depending on what is possible or desirable" (Reif and Larkin, 1991, p. 742). Although they do not explicitly define characteristics of scientific explanations, they implicitly use consistent criteria which include a logical structure with: multiple ways of interpreting, describing, and reducing a case to a simple model, assessment of applicability of alternatives models, and some esthetic considerations. This conclusion is based on data from the field of physics. More research is needed for extrapolating to other disciplines.

Scientific Explanation and Science Education

Although science educators agree with philosophers that explanation is the very purpose of science itself (Dagher & Cossman, 1992), little research is done on the nature of explanation from the point of view of science education. Most of our understanding of scientific explanation of phenomena is derived from the philosophy of science. Understanding the nature explanation

[2] APS Texas Section Meeting, Austin, TX, October 13-14, 1994

from a philosopher's perspective provides an analytical base for such inquiry, but the locus of interest of science education is different: we need to apply and extend such understanding to particular cases related to teaching and learning. After a discussion of science educators views of scientific explanation, empirical findings on the nature of explanations found in science learning and teaching are reviewed here.

Science Educators Views on Explanations

Rather concerned with instructional practices, science educators appear to deal with theoretical models of explanation at less profound, less coherent, and less elaborated levels than philosophers do. Research on scientific explanations in science education seems to operate under the following assumptions: (1) Description is associated with observation and often considered to be distinct from theory. Explanation is associated with scientific theory. (2) The character of explanations used in teaching expresses implicit messages about the nature of science promotes different curriculum emphases (goals), and assigns a different role to the teacher. (3) Explanation of phenomena is used to assess students understanding essentially in the expert-novice tradition (with the Teacher=Expert and the Student=Novice).

What types of explanations are there?

As a science educator and curriculum philosopher, Horwood (1988) alluded to the relationship between teachers' explanations and "curriculum emphases" defined by Roberts (1982). They include three kinds of explanations, each of which induces a different picture of science and assigns a different role to the teacher. Yet, Horwood emphasized the distinction between *research explanations* and *teaching explanations* . In his view, research explanations are only *of something*, while teaching explanations are also *for someone*. Furthermore, research explanations "need not be concerned with whether or not the audience, if any, has understood the explanation" (p. 43). In contrast, Horwood contends that teaching explanations have to satisfy contradictory demands that "the learner gain understanding (leaving no unanswered questions), without inhibiting future learning" (p.43).

Horwood's view of research explanations is not consistent with Achinstein's general model $E=f(A, q, S)$ requiring S be always satisfied. Furthermore, it discards requirements for inter subjectivity and communication in science implying ideas about the nature of science which one may find questionable.

Is Explain the same as Describe?

Horwood (1988) draws a sharp demarcation between *description* and *explanation* of phenomena, suggesting some absolute factual core to be independent from theories, and concluding that textbooks and tests introduce confusion by using the terms interchangeably. He proposes to define descriptions as "pure information isolated and without a network of relatedness" while "explanations have information with connections, a relationship built on a system of causality" (p. 41). Postulating a similar, dualism between *describe* and *explain*, Pallrand (1993) concluded that students confuse *what*-questions (observe/describe) with *why*-questions (explain), thus laying the foundations for absolute facts in school science. This is of course in contradiction with the conception expressed by Reif & Larkin (1991) which is consistent with a modern interpretation of Hempel & Oppenheim's (1988/1948) D-N model: it involves inferences showing how observable phenomena can be deduced from basic premises, thus assuming a continuum between *observe*, *describe*, *explain*, and *predict*..

Other studies.

From a more philosophical stand point, Ohlsson (1992) reminded us that an explanation is not accomplished by merely repeating the general principles of the theory. These have to be instantiated with respect to the particular phenomenon. He reintroduced Kuhn's (1960) notion of *theory articulation* to denote this activity, which involves applying a theory to a particular situation, to decide how, exactly, the theory should be mapped onto that situation, and to derive what the theory implies or says about the situation Noting that many scientists do not spend their time making new empirical discoveries, but rather incorporating known phenomena to existing theories, Ohlsson argues that scientific literacy requires that students not only learn the methods of empirical inquiry, but also learn how to articulate theories.

Empirical Studies of Explanations

The nature of explanations in teaching.

Horwood's (1988) analyzed the activities and the terminology used in teaching and in textbooks. He found cases where a request for explanation (in testing materials) was best understood as a request for a definition, and other cases making reference to chains of causality. Assuming his definitions of *describe* and *explain*, he also found teachers and students using the description of an event or a process as equivalent to explaining it. In other examples, he found contradictory explanations in different textbooks (biology, chemistry) concluding that the terms "describe" and "explain" and the activities of description and explanation were used in "variable, inconsistent, and confusing ways" (p. 48). Unfortunately, the sources or methods used were not specified.

Although the subject of teachers' explanations is very broad, many of them deal with uses of particular types of explanation like metaphors or analogies, but again they treat essentially the pedagogical aspects. For example, Thagard (1992) shows how the strengths of particularly good analogies and the weaknesses of particularly bad ones can be understood and suggests lessons for how analogies can most effectively be used in instruction. Thiele and Treagust (1994) also investigated the use of analogies in chemistry teaching and their power as pedagogical tools. One study was found to deal with the nature of teachers' explanations. Dagher & Cossman (1992) analyzed 20 teachers' discourse from data collected in middle school science classrooms. They identified nine types of teachers' explanations for phenomena, which they classified as *analogical, anthropomorphic, functional, genetic, mechanical, metaphysical, rational, tautological, and teleological*. A closer look at the reported results indicates that most of the explanations regardless of the disciplines were of two types: mechanical (causal) or genetic (relating to an antecedent sequence of events); and a significant number of them was classified as analogical (a correspondence assumed to exist between aspects of a (familiar) situation and those of the actual phenomenon).

The nature of individuals' explanations of phenomena.

Research on "children science" (Osborne & Freyberg, 1985) investigated children's views of the world and the meanings for words that children. Other studies (by Driver, Stavy, Carey, Linn, Gunstone, and others) investigated students understanding of specific concepts or views of science. For example, Solomon (1995) investigated the ability of high school students to deal with epistemological questions about models, interpretations, and explanations. Except for the application of their probing methods, studies in this line of research did not appear to be relevant to the nature and structure of explanations likely to be developed by individuals who have received different amounts of science instruction. Although individuals' views of science have been studied for many years in science education (e.g., Kimball, 1968), few studies were found in the literature that investigated the nature and structure of explanations provided by individuals of various backgrounds and in diverse settings. The few qualitative studies that were founde are summarized below and in the table. They defined ad-hoc categories for classifying individuals' explanations.

Metz (1991) investigated change in the physics knowledge of young children and examined the explanations of jamming gears generated by 32 children, 3 to 9-year old. Three developmental phases were identified: function of the object as explanation, connections as explanations and mechanistic explanations. Tamir and Zohar (1991) found that secondary school students in biology applied *teleological* and *anthropomorphic* reasoning to explain plants and animals phenomena. Touger, Dufresne, Gerace, and Mestre, (1995) classified college students' explanations in physics as *intuitive, formula driven*, or *hierarchical*. Finally, Edgington and Barufaldi (1995) investigated explanations generated by individuals who were not novices in physics about a well known physics demonstration. They found explanations at various levels of complexity. Gavenda and Edgington (in press) discuss these levels of complexity with regards to lecture demonstrations.

Representative studies of individuals' explanations

Study	Topic of the study	Nature of Explanation
Metz (1991)	3-9 year old children (developmental) Jamming gears	Function Connections Mechanistic
Tamir & Zohar (1991)	secondary students' reasoning Biology	no anthropomorphism, but teleology applied to plants and animals
Dagher & Cossman (1992)	middle school teachers Life and Physical Science	analogical, anthropomorphic, functional, genetic, mechanical, metaphysical, rational, tautological, teleological
Mestre, Touger, Dufresne, Gerace, ...	college physics students Classical Mechanics	intuitive formula driven hierarchical
Edgington & Barufaldi (1995)	physical science teachers	verbal, pedagogical, or mechanical
	high physics school teachers	single model, deductive, formula driven
	graduate students (physics)	single model, hierarchical, deductive
	research physicists	multiple models, hierarchical, limitations emphasized

The number of studies of this type is insufficient to provide a guiding framework to the study of explanations in science education. Each study dealt with diferent groups of individuals in differnt contexts. This diversity indicates that further research will enrich this area of science education in a number of ways: It will contribute to develop a research framework for explanation of natural phenomena that will serve to analyze and guide instruction at different ages and in different disciplines.

In Conclusion (Science Education)

Science educators' views on explanation are less profound, less coherent, and less elaborated than those of philosophers. Some science educators assume a duality between teaching explanations and research explanations which leads to confusion about the nature of science. Also, they draw a demarcation between description and explanation. Furthermore, the scientific theory invoked in an explanation and the scientific explanation as an interpretive application of the theory appear to be confused, often implying that *the theory is the explanation.* This raises concerns about alternative conceptions studies, where science educators' views on these issues are the basis for interpreting students' explanations.

The views on explanations held by physics education researchers (PER) are congruent with the D-N model as an ideal. Beyond inferences of the explanandum from theoretical premises and initial conditions, these views include additional criteria for scientific explanation. They emphasize the need to assess the validity of the descriptive statements and to specify that different theoretical premises may account for the same phenomenon.

Discussion

Answers to the question "What is a scientific explanation" cover a broad range of possibilities. Philosophical analyses identify the pragmatic factors involved in the explanation as well as the logical structure of ideal explanations. Research physicists apply the D-N model in practice (though they may not know it by name): They view explanations as part of playing by the rules of the scientific domain which are very distinct from those we use in everyday domains. Studies in the nature of explanation in science education stand on looser philosophical grounds. Science educators appear to be still sorting out the parameters of the $E=f(A, q, S)$ model of explanations in general. Although they use students explanations to research their conceptual understanding, they deal very little with models of scientific explanations. Most of the studies in this area of science education are interested in types of teaching explanations and their effectiveness. Few studies investigated the nature of explanations generated by diverse groups of individuals in various settings.

According to Horwood (1988), science education researchers need to deal more with explanations, their character, and their influence on the curriculum. Indeed, explanations of particular phenomena are used everyday for delivery and for assessment of instruction in science. For example, scientific explanations are part of lecture demonstrations, science classroom experiments, educational and curricular materials, and tasks used for the assessment of students understanding. These instructional and research practices convey messages about the nature of science in every particular case. Therefore, fundamental questions will need to be clarified in the first place: What is the nature of these explanatory arguments and what are the grounds for analyzing their quality?

PER's views provide an initial framework for science education research on explanations proposed by individuals who have received formal instruction in physics. How can this framework be modified and extended to include uninstructed individuals and younger students? Is it applicable to other disciplines and in different settings? Research work reported by Tamir and Zohar (1991) and by Dagher and Cossman (1992) provide grounds for beginning to answer these questions. However, the results of this review suggest that the potential in this area of research has yet to be recognized.

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